CHAPTER 5

ENGINEERING CONSIDERATIONS PERTAINING TO CONSTRUCTION

5-1. General. This chapter addresses engineering considerations pertaining to the construction of pile foundations. It is important for the designer to become familiar with the various equipment (Items 31 and 32) and methods used during construction since either may adversely affect soil-structure interaction, economics, and the overall effectiveness of the design. Early in the design process consideration should be given to available pile materials and lengths, appropriate construction methods and equipment, load tests, acceptable and achievable construction tolerances, and maintaining quality control and records during construction. Design coordination with construction should begin in the early design stages. These considerations, combined with past experience, should result in the formulation of an appropriate foundation design and the preparation of suitable construction plans and specifications. Upon completion, a review of construction variations should be made to determine if an as-built analysis is warranted. Material presented in this chapter is intended to give design and construction engineers an overview of installation and its effect on the design. Detailed discussions can be found in the literature and the cited references.

5-2. Construction Practices and Equipment. A variety of methods and special equipment have been used for the installation of piles. Many factors are involved in the selection process, but the end result should always be structurally sound piling supported by soil or rock that is capable of developing the design loads. To achieve this result, it is imperative that the specifications provide for use of appropriate installation methods, suitable equipment, and acceptable field procedures. Contract specifications should be as flexible as possible so that economy is achieved, yet rigid enough to result in the desired final product.

a. Installation Practices. Installation practices include consideration and utilization of appropriate field methods for storing, handling, and accurately driving each pile to the desired final position within established tolerances. Specifications typically outline requirements for the contractor to submit his proposed plan for installing the pile. Required submittal items normally include detailed descriptions for pile storage and handling, the driving rig and all auxiliary equipment (with manufacturer’s specifications and ratings), installation sequence, methods for controlling placement and alignment of piles, and, if permitted, the pile splice types, locations and plan, and quality control plan. In addition, the specifications normally require submittal of data for a Government-performed wave equation analysis. Government review should focus on the contractor’s compliance with the specifications and the ability of his proposed equipment and methods to produce structurally sound piling, driven within the established tolerances and capable of developing the required design capacity. Installation methods or equipment suspected of compromising the foundation design should be clearly excluded by the specifications. The contractor may question those exclusions and may substantiate his claim at his expense by performing wave equation analysis, field verification of driving and static load tests, dynamic monitoring, or other methods designated by the designer.

(1) Storage and Handling. Piles are subject to structural damage during the storage and handling processes. Improper storage or handling may result

in excessive sweep (camber) or cracking in concrete and may be cause for rejection of a pile. Excessive sweep, or camber, has been known to result in a pile drifting out of tolerance during installation. Sweep and camber limitations should be included in the specifications. Stresses developed during the storage and handling phases should be investigated and compared to those allowed in paragraph 4-2d. Additionally, both the required number and locations of permissible pick-up points on the pile should be clearly indicated in the plans and specifications. Any deviations in the field must be approved by the design engineer. Special care must be exercised when handling piles with protective coatings, and damaged areas must be repaired prior to installation. All pilings should be visually examined at the driving site by a qualified inspector to prevent the use of any pile damaged by faulty storage or handling procedures.

(2) Placement and Tolerances. When determining suitable placement tolerances, consideration should be given to the site conditions, i.e., topography; subsurface materials; type of loading; pile type, spacing and batter; size and type of pile cap and structure; available driving equipment; and possible interference between piles. A lateral deviation from the specified location at the head of not more than 3 to 6 inches measured horizontally and a final variation in alignment of not more than 0.25 inch per foot measured along the longitudinal axis should normally be permitted. In the vertical direction a deviation of plus or minus 1 inch from the specified cutoff elevation can be considered reasonable. The above recommendations are general guidance for large pile groups and should be verified as applicable for each specific project. It should be noted that sloping surfaces may require field adjustment of the pile location if the actual excavation line differs from the reference plane used in the plans to depict pile locations. Each pile should be checked in the field prior to driving. The pile head should be seated in the hammer and the pile checked for correct batter, vertical plumbness, and rotation of the pile by a method approved by the design engineer. Many jobs require the use of a transit to set the pile and the leads accurately when driving battered piles. Once driving has commenced, attempts to move the pile by rotating the leads, pulling on the pile, or wedging may result in damage (structural or soil alteration) or increased misalignment of the pile tip.

(3) Driving. Contract specifications disallow field driving of piles until the contractor’s methods and equipment are approved by the design engineer. Designer approval is necessary to ensure the pile can be driven without damage to the pile or soil, and methods for determining such are discussed in paragraph 5-3. The designer should be aware that certain equipment and methods for pile installation have been known to reduce axial and lateral resistance or damage the pile in certain situations. Field variations from the approved methods and equipment require re-submittal to the design office, as changes can and usually do effect the pile capacity attained for a given length pile. It is incumbent upon the designer to supply field personnel with the necessary information to ensure each pile installed is capable of supporting its design load. Such information most often consists of limiting penetration resistances (paragraph 5-3) or the specification of a pile driving analyzer (paragraph 5-4a) to prevent structural damage from overdriving and to ensure that adequate capacity is developed. Field personnel must ascertain the equipment and installation methods are properly employed, the equipment is performing up to its capabilities, records are properly kept (paragraph 5-4b), and any driving abnormalities are promptly reported back to the design office. Pile driving should not result in crushing or spalling of concrete, permanent

deformation of steel, or splitting or brooming of wood. Damage sustained during driving can frequently be attributed to misalignment of the pile and hammer, a material failure within the drive cap, equipment malfunction, or other improper construction practices. Field installation requires diligent monitoring of penetration resistance. Any piling suspected of either sustaining structural damage or failing to develop the required capacity, for whatever reason, must be promptly evaluated by the designer to determine its effect on the overall foundation design. Repetitive problems may require modification of the installation equipment or procedure. Pile heave can be a problem in some cases and is more inclined to occur for displacement piles. In this case, an installation sequence should be required to minimize the likelihood of pile heave. Piles that experience heave should be restruck to seat the pile properly. The installation of a concrete pile requires special consideration due to its inherent low tensile strength. The pile must be firmly seated prior to the application of full driving energy to prevent pile cracking or breakage. Pile driving can sometimes be supplemented by special driving assistance such as the addition of driving shoes, jetting, preboring, spudding, or followers. The use of special assistance should be considered when one of two conditions exist. If a pile reaches refusal with a suitable hammer but does not achieve the necessary capacity, a modification to the installation procedures may be necessary. Simply increasing the size of the hammer may not be appropriate because the pile would be damaged due to excessive driving stresses. The second condition is an economic one, where the installation time and effort can be substantially reduced by the modifying installation procedures. In either case, the potential effect on the axial and lateral pile capacity must be closely evaluated. Contract specifications should define as clearly as possible what type of special driving assistance, if any, would be allowed and under what conditions they would be allowed. Since methods of providing special driving assistance usually result in reduced pile capacity, specifications normally preclude their use without written approval from the designer. Methods and rationale for the selection of equipment, field inspection, establishment of penetration limitations, record keeping requirements and methods for controlling the driving operation are contained elsewhere in this chapter.

(a) Pile shoes. Pile shoes are frequently used to improve driveability and also provide protection at the pile tip. When driving piles in dense sands, in hard layers containing cobbles or boulders, or through other obstructions, increased cutting ability and tip protection are provided by the shoe. Piles seated in rock normally require shoes for tip protection and improved bearing characteristics. Steel pile shoes are usually fabricated of cast steel, particularly for steel H-piles, where plates welded to the flange and web have proven unreliable. The design engineer should evaluate the necessity and cost of using pile shoes on a case-by-case basis.

(b) Jetting. Jetting is normally used when displacement-type piles are required to penetrate strata of dense, cohesionless soils. Exceptions are very coarse or loose gravel where experience shows jetting to be ineffective. Piles, in some cases, have been successfully jetted in cohesive soils but clay particles tend to plug the jets. Jetting aids in preventing structural damage to the pile from overdriving. Water is pumped under high pressure through pipes internally or externally attached to the pile, although air may be used in combination with the water to increase the effectiveness in certain cases. The last 5 to 10 feet of pile penetration should be accomplished with no jetting allowed. Piles that cannot be driven the last 5 to 10 feet without the aid of jetting should be immediately brought to the attention of the design engineer, since a reduction in axial capacity will probably result. When jetting concrete piles, driving should be restricted to a static weight while the water is being injected to prevent damage due to excessive tensile stresses that may be induced by impact. Jetting adjacent to existing structures or piles should be avoided if possible. Although driving vibrations are reduced, extreme caution must be exercised, since jetting causes disturbance of soil material. The design engineer must exercise caution when determining the design capacity for a jetted pile. Adequate provisions must be made for the control, treatment (if necessary), and disposal of run-off water. If jetting is anticipated, test piles should be installed using jetting, with the test pile being installed after the reaction piles are installed to assess the effects of jetting on capacity.

(c) Preboring. A pilot or prebore hole may be required to penetrate hard nonbearing strata; to maintain accurate location and alignment when passing through materials which tend to deflect the pile; to avoid possible damage to adjacent structures by reducing vibrations; to prevent heave of adjacent buildings; or to remove a specified amount of soil when installing displacement-type piles, thereby reducing foundation heave. Preboring normally takes place in cohesive soils and is usually required when concrete piles must penetrate man-made fills and embankments containing rock particles or other obstructions. It should be noted that on past Corps projects, concrete piles have been successfully driven through man-made fills such as levee embankments without preboring. Preboring through cohesionless soils is not recommended, since the prebored hole may not stay open and could require a casing. The most widely used method of preboring is by utilizing an auger attached to the side of the crane leads. When preboring is permitted, the hole diameter should not be greater than two-thirds the diameter or width of the pile and not extend more than three-fourths the length of the pile. Oversizing the hole will result in a loss of skin friction and a reduction in the axial capacity and lateral support, thereby necessitating reevaluation of the pile foundation. When extensive preboring is needed, consideration should be given to using a drilled-shaft system rather than a driven-pile system.

(d) Spudding. Spudding is similar to preboring and may be appropriate when layers or obstructions are present near the surface that would damage the pile or present unusual driving difficulty. Spudding is accomplished by driving a spud, such as mandrel, heavy steel pipe or H-pile section, to provide a pilot hole. The spud is withdrawn and the pile inserted into the hole and driven to the required depth. Problems may result if the spud is driven too deep, since extraction becomes more difficult as penetration is increased. Spudding may sometimes entail alternately lifting a partially driven pile a short distance and redriving it when very difficult driving is encountered (e.g. for heavy piles). Because this procedure adversely affects the soil's lateral and axial capacity, it should be avoided for friction piles and should never be permitted without the specific authorization of the design engineer.

(e) Followers. A follower is a member placed between the pile hammer and pile that allows the pile to be driven below the reach of the leads. The most common uses are to drive a pile below the top of an existing structure or for driving piles over water. Although the follower can make driving less difficult, there are several problems associated with their use. Experience shows it to be quite difficult to maintain alignment between the pile and follower, especially for battered piles. Additionally, erratic energy losses due to poor connection between the pile and follower, frequent misalignment, and follower flexibility make it nearly impossible to equate blow count with pile capacity. For these reasons most specifications exclude the use of followers. If a follower must be used, it should be selected so that it's impedance is between 50 and 200 percent of the pile impedance. The impedance is defined as EA/c where E is the modulus of elasticity of the material, A is the cross sectional area, and c is the velocity of wave propagation for the material. If concrete piles are being driven, then some cushion must be used between the follower and the pile.

(4) Extraction. Extraction, or pulling of specific piles for inspection, may be required when unusually difficult driving conditions have been encountered and pile damage is suspected. Extraction and redriving may also be necessary when a pile drifts excessively during driving and fails to maintain the specified placement tolerances discussed in paragraph 5-2a(2). When excessive drift occurs, the circumstances should be carefully investigated to determine the cause and appropriate remedial measures specified. Pile extraction is usually difficult, expensive, requires special equipment and experienced personnel. A large pulling force concentric with the longitudinal axis of the pile must be exerted continuously in addition to application of hammer energy in the same direction. Extraction can be assisted by jetting, especially when removing low tensile strength piles such as concrete. See paragraph 5-2b(2) for a discussion of equipment required for extraction.

(5) Underwater Driving. Occasionally piles must be driven below the water surface at a location where site dewatering is not economically feasible, e.g., navigation fenders, dolphins, guide walls, piers, etc. Commonly, pile driving equipment is placed on barges and positioned at the work site with tug boats. A special templet is normally utilized to maintain the designated position and alignment of the piles during driving. Placement tolerances are usually less stringent for these structures. When the pile head must be driven below the water surface, a follower with a special connection to the pile head may be used. In some cases a hydraulically driven, submersible pile hammer (clamped to the pile head) may be used, especially if the pile head must be driven a substantial distance below the water surface. For example, a submersible hammer would be appropriate to drive steel piles to the mudline for anchoring mooring buoys that have substantial design loads and the accuracy of placement position is not critical.

b. Equipment. Piles are normally driven by impact or vibratory-type hammers. Typical driving equipment consists of a crawler-mounted crane with a boom, leads, hammer, and various accessories, each connected to act as a unit. The equipment serves to guide and drive each pile accurately into its final position and must be strong enough to withstand safely all loads imposed during the process. The crane and boom must have adequate size, capacity and connections to handle the pile and the special driving equipment, such as the hammer or extractor, leads, and accessories, safely. Considerable engineering experience and judgement are necessary when evaluating or specifying the suitability of driving equipment. Supplemental information is normally available in the form of technical literature provided by the equipment manufacturer. Only equipment anticipated to be detrimental to the pile, soil, or soil-pile interaction should be excluded by the construction specifications. A discussion of hammer selection is presented in paragraph 5-3b. Safe equipment operation must also be considered in the design and construction phases of a project. Common situations that typically require special safety precautions are obstructions (such as overhead or buried electrical lines), driving on slopes or near the edges of excavations, and possible crane overturning. Specific safety requirements are contained in EM 385-1-1.

(1) Hammers. Hammers can generally be divided into two groups, impact and vibratory. Impact hammers may be lifted manually or automatically by steam, air or diesel, and may also be single or double-acting. These hammers are sized by the maximum "rated energy" (foot-pounds) theoretically contained as kinetic energy in the ram just before impact. This rated energy is not necessarily absorbed by the pile. Vibratory hammers are electrically or hydraulically powered, usually have a variable operating frequency range (vibrations per minute), and are generally rated by "eccentric moment" (inch-pounds) and "driving force" (tons) for a specified frequency. Literature providing specific properties for currently available hammers may be obtained on request from the hammer manufacturer or distributor. The hammer approved for use should be examined in the field to assure that the hammer is in good condition and operating as close as possible to its rated capacity in accordance with procedures provided by the manufacturer. Hammer efficiency may be influenced by items such as the operating pressure, wear of moving parts, lubrications, drive cap cushions, driving resistance, batter angle, and the relative weights of the hammer and pile. Operating pressure at the hammer (for steam and air hammers), stroke distance and operation rate (blows per minute) must be checked regularly while driving piles with any type of impact hammer. Variations in these values usually signify changes in hammer energy and efficiency, or pile damage. Steam- or air-powered automatic-type hammers also require special supplemental equipment, including adequately sized hoses, power source and fuel, and self-powered air compressor or boiler with a water supply for steam. A brief description of the various hammers and general recommendations follow. Item 31 contains an excellent discussion of hammer operation and suggested inspection techniques.

(a) Drop Hammers. The drop hammer is the simplest and oldest type of impact hammer. It consists of a guided weight (ram) that is lifted to a specified height (stroke) by a hoist line and released. Drop hammers are operated by raising the ram with the crane and then, at the desired height as judged by the crane operator, dropping the ram by allowing the winch to spool. Some of the available energy is used as kinetic energy in the winch and is not actually available to drive the pile. Drop hammers can damage the pile head if driving stresses are not controlled by limiting the stroke distance and supplying a cushion material (hammer cushion) between the anvil, which sits on the pile head, and ram. Theoretical or rated hammer energy is the product of the stroke times the ram weight. To arrive at actual energy delivered to the pile, proper allowances must be made for the effects of friction and interaction of the drive cap. The drop hammer is a comparatively simple device that is easily maintained, portable, relatively light, and does not require a boiler or air compressor. The drop hammer is most suitable for very small projects that require relatively small, lightweight timber, steel, or aluminum piles. Due to its slow operating rate, usually 5 to 10 blows per minute, this type of hammer is used only when the cost of bringing in a more sophisticated hammer would not be economical.

(b) Single-Acting Steam or Air Hammers. The single-acting hammer as shown in Figure 5-1 has been in use for many years, has been extremely well developed and can be used for most any pile-soil combination. This hammer type utilizes pressure from steam or compressed air to raise the ram, then

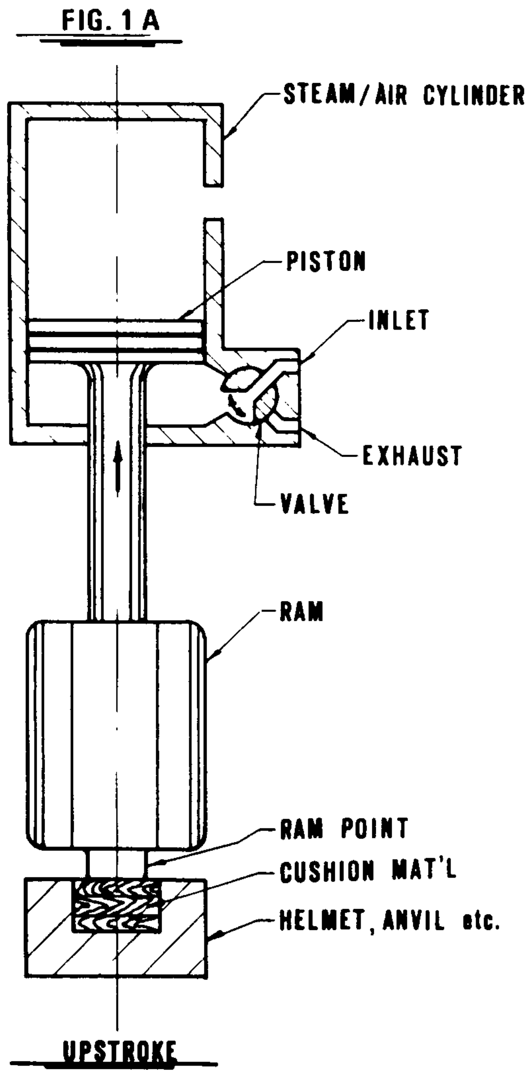


Figure 5-1. Single-acting steam/air hammer (Permission to reprint granted by Deep Foundation Institute (Item 31))

automatically releases the pressure allowing the ram to fall freely and strike the drive cap. Hammer operation is automatic and generally in the range of 40 to 60 blows per minute. In comparison to the drop hammer, single-acting hammers operate at much faster speeds, have shorter stroke distances and possess considerably larger ram weights. A hammer cushion may or may not be utilized within the drive cap, and its use is largely dependent on the recommendations of the hammer manufacturer. Hammer efficiency can be checked by observation of the ram stroke and hammer operation rate. If the hammer maintains the specified stroke and operating speed, it can be reasonably assumed the hammer is functioning properly. A single-acting hammer may lose considerable driving energy when used to drive battered piles. This energy loss can be attributed to a reduction in the height of the ram's vertical fall and increased friction between the piston and cylinder wall and between the ram and the columns.

(c) Double-Acting Steam or Air Hammers. Double-acting and differential-acting hammers, as shown in Figures 5-2 and 5-3, utilize pressure from steam or compressed air to raise the ram in a manner similar to a single-acting

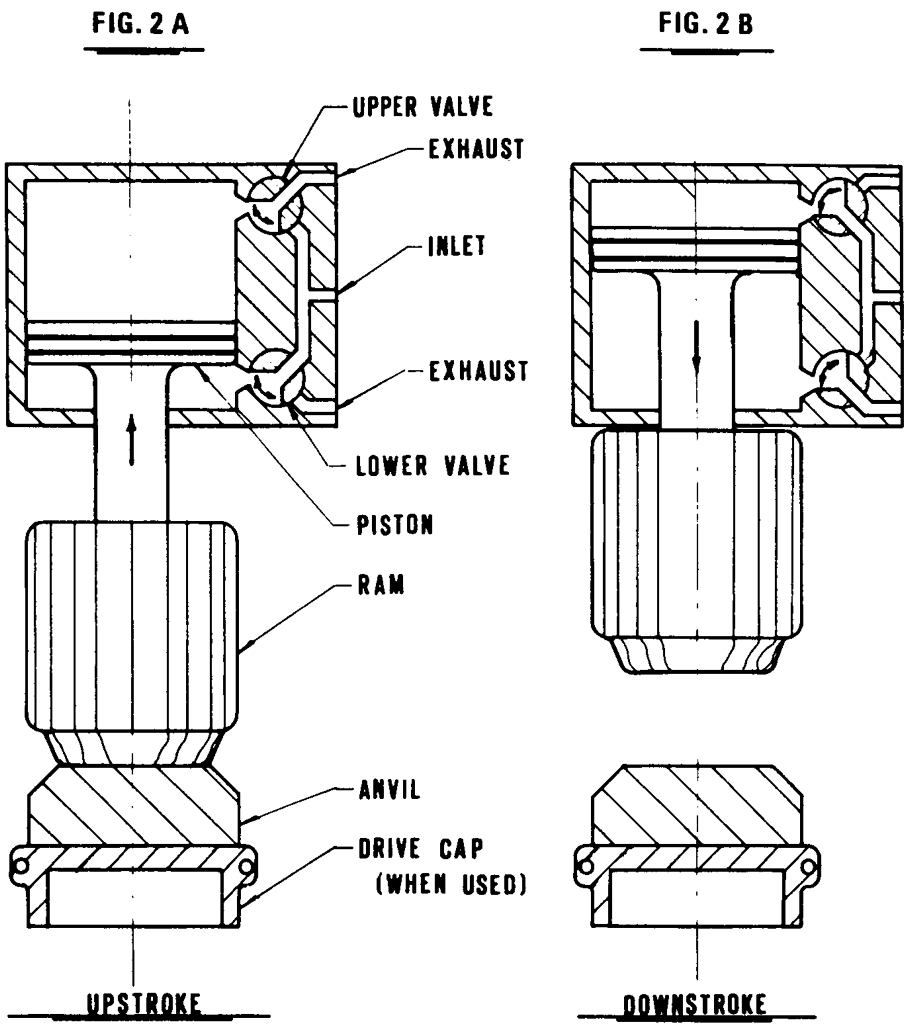


Figure 5-2. Double-acting steam/air hammer (Permission to reprint granted by Deep Foundations Institute (Item 31))

hammer. The steam or compressed air is also utilized to supply additional energy to the ram on the downward part of the stroke. The combination of pressure on the downstroke and a short stroke distance results in an operating rate generally ranging from 90 to 150 blows per minute. These hammers can deliver impact energies comparable to the single-acting hammers at approximately 1.5 to 2.0 times the operating rate. Although the high operation speed is beneficial to production, it generates relatively high impact velocities and stresses, which may result in pile-head damage to piles of low compressive strength. A hammer cushion material is not used between the ram and pile helmet for the double-acting hammer but is required for the differential-acting hammer. The types of impact hammers are normally closed at the top, and the stroke cannot be monitored during driving. Actual field operation should be at the full hammer speed as listed by the manufacturer, since the rated hammer energy quickly reduces at lesser speeds. Rated energy and efficiency values provided by the manufacturers can be misleading, and the engineer must be cautious and use appropriate judgement when calculating the energy actually transferred to the pile during driving. These hammer types may be used without leads (when not required for piles) and may be inverted and rigged for use as pile extractors. Best performance is usually obtained

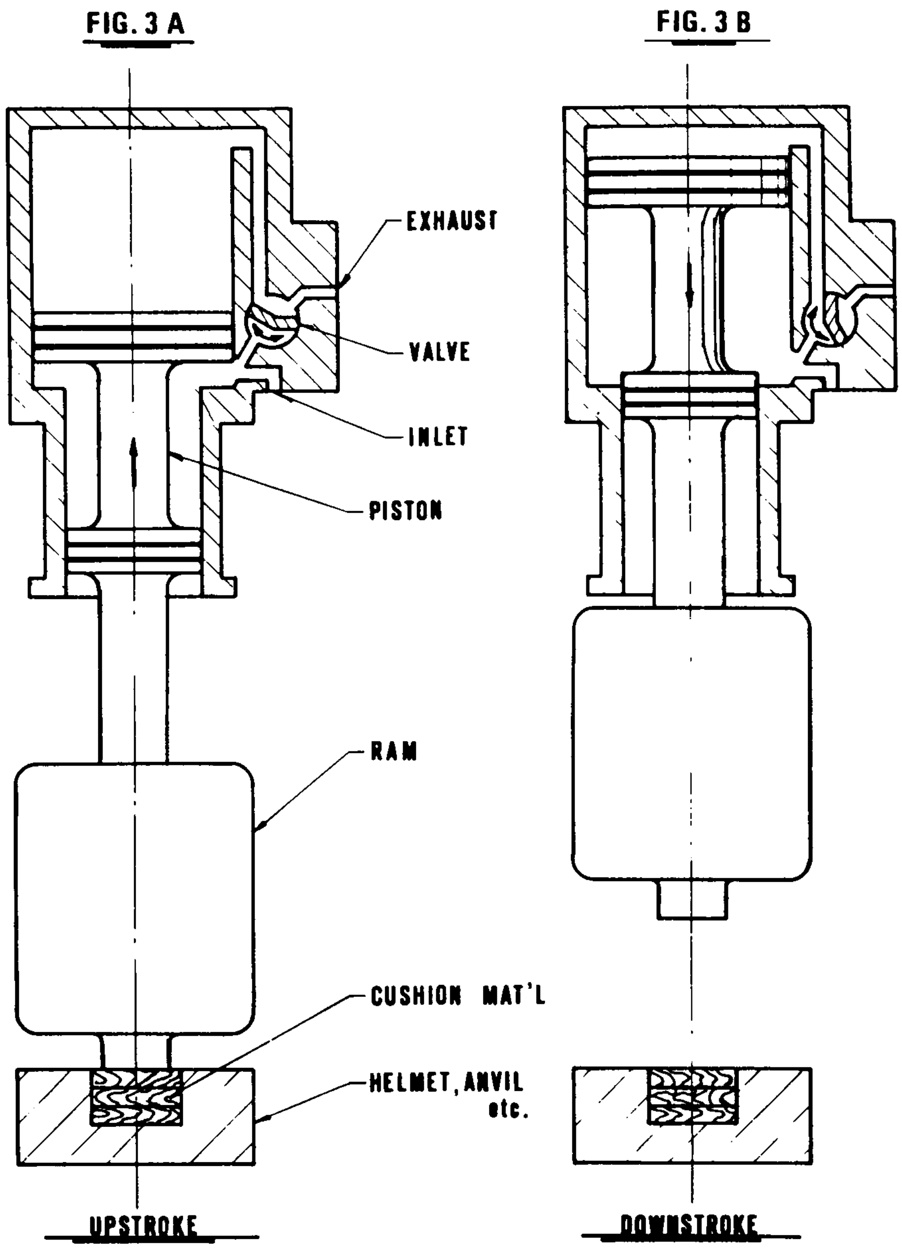


Figure 5-3. Differential-acting steam/air hammer (Permission to reprint granted by Deep Foundations Institute (Item 31))

when driving wood or nondisplacement steel piles into sands, but the hammers may be used in any type soil.

(d) Open-End Diesel Hammers. The open-end diesel hammer (Figure 5-4), also known as the single-acting diesel hammer, is self-contained, economical, light in weight, and easy to service. The fuel is injected into the cylinder while the ram drops. When the ram strikes the anvil the fuel is atomized and ignited, explodes and forces the anvil down against the pile and the ram up. This supplies energy to the pile in addition to that induced by impact of the ram. The sequence repeats itself automatically provided that sufficient pile resistance is present. Hammer efficiency is a function of pile resistance and therefore the harder the driving the greater the efficiency. Diesel hammers can be equipped to permit the amount of fuel injected into the cylinder to be

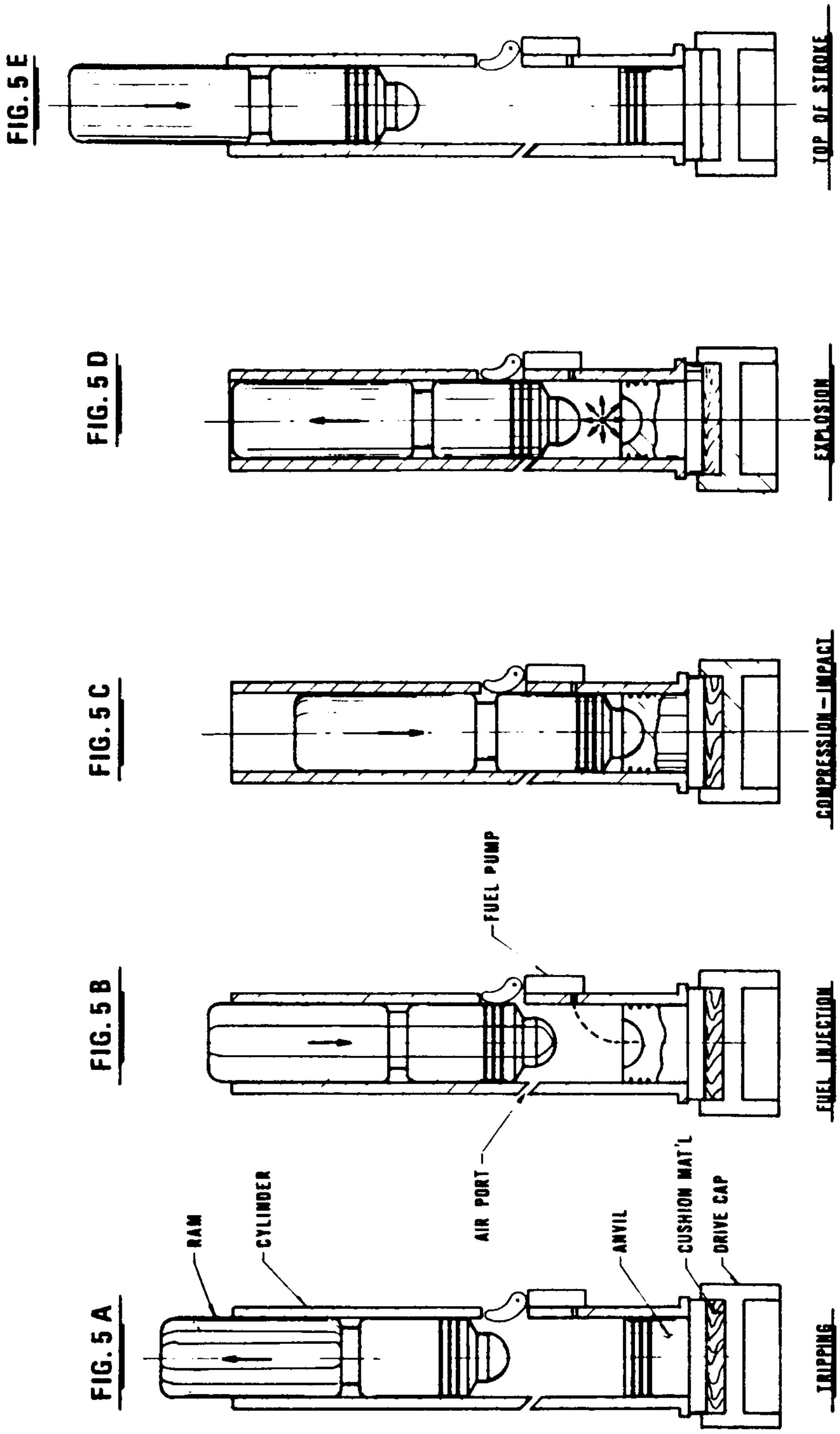


Figure 5-4. Open-end (single-acting) diesel hammer (Permission to reprint granted by Deep Foundations Institute (Item 31))

varied. This feature can be an asset when initially seating concrete pile. The energy transmitted to the pile can be controlled by limiting the amount of fuel supplied to the hammer, thereby yielding some control on the critical tensile stresses induced by driving. Diesel hammers combine medium ram weights and high impact velocities. The open-end diesel hammer requires a cushion material (hammer cushion) between the anvil and the helmet. Operating speeds are somewhat slower than the single-acting air-stem hammer ranging from 40 to 50 blows per minute. As the driving resistance increases, the stroke increases and the operating speed decreases. Proper maintenance and operation of the diesel hammer is a necessity. Open-end diesel hammers are best suited for medium to hard driving conditions. They do not tend to operate well in soft soils because of the driving resistance required for compression and ignition.

(e) Closed-End Diesel Hammers. The closed-end diesel hammer, Figure 5-5, also known as the double-acting diesel hammer, is similar to the open-end hammer, except that a closed top and bounce chamber (air tank) are provided at the upper end of the cylinder. The stroke is shortened from that of the open-end hammer by creating a cushion of compressed air in the bounce chamber and between the ram and the closed upper end of the cylinder. This results in operating speeds of about 80 blows per minute. Some closed-end hammers are convertible to the single-acting mode, thereby giving the contractor further flexibility. Requirements for cushion materials, leads, maintenance, and operation are similar to those of the open-end diesel hammer.

(f) Vibratory Hammers. Vibratory hammers are available in high, medium, and low frequency ranges. High-frequency hammers are commonly known as "sonic hammers." The sonic hammer has had limited success and is seldom used. Vibratory hammers operate by utilizing electric or hydraulic motors to rotate eccentric weights and produce vertical vibrations as shown in Figure 5-6. The vibrations reduce frictional grip of the soil and also permit the soil at the tip to be displaced. Additional biased static loads can often be provided by dead weight to enhance drivability. Leads are not required for use of a vibratory hammer but are normally required for desired driving accuracy. It is important that a rigid connection be maintained between the hammer and the pile, usually by means of a mechanical clamp, and a back-up system may be required to prevent release of the clamp in the event of a power failure. Vibratory hammers are most efficient for installing non-displacement type piles in sand. Clay soils tend to dampen the vibration of the hammer, thereby retarding penetration. When used in clay materials, the low frequency hammer has been more successful since it has more of a chopping effect than the medium-frequency hammer which is normally used for sands. These hammers are not very effective in penetrating obstacles, large cobbles or stiff clays. Vibratory hammers are generally not suitable for the installation of most concrete piles and are seldom used on timber piles. When used for the right combination of pile and soil, vibratory hammers can install production piles at a rate much faster than any type of impact hammer. For example, it would not be uncommon to drive a 60-foot steel H-pile in sand in less than 5 minutes. An added advantage of the vibratory hammer is that it can extract piles as easily as it can drive them, requiring no new equipment set-up. Vibratory hammers and their limitations are discussed in paragraph 5-3b.

(2) Extractors. The extraction of piles can be difficult and usually requires special equipment and experienced personnel. Extractors can be classified as either impact or vibratory type. The impact type operates similar

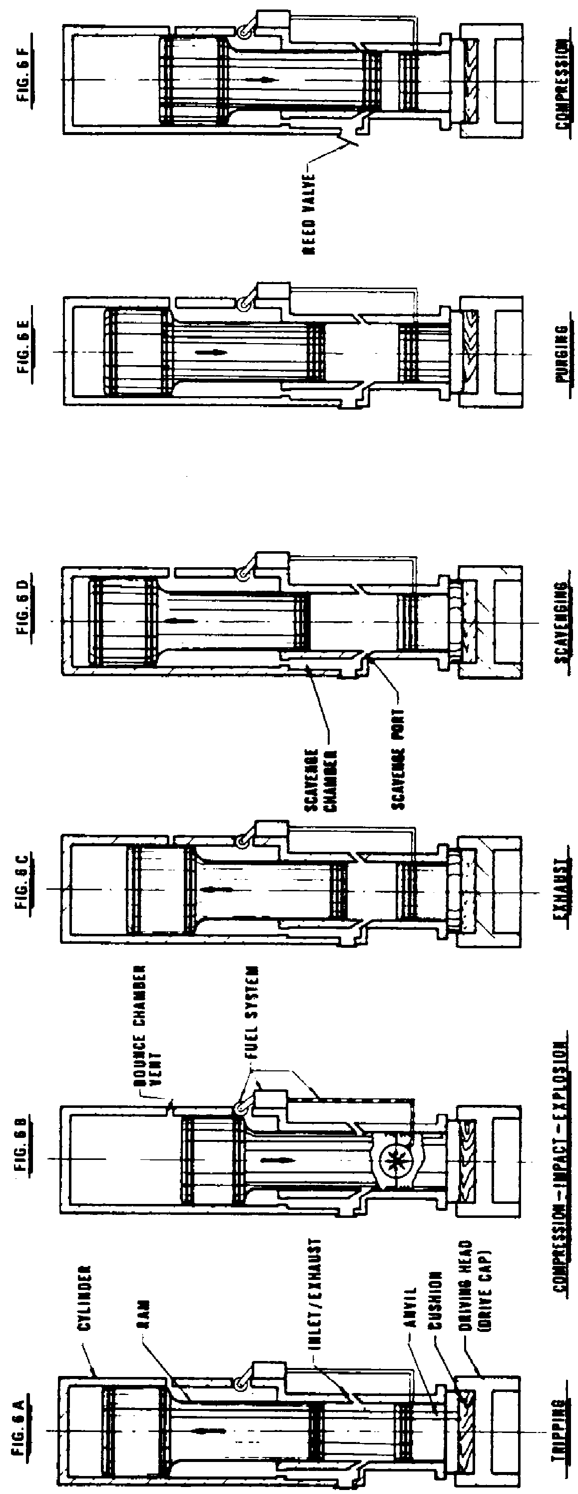


Figure 5-5. Closed-end (double-acting) diesel hammer (Permission to reprint granted by Deep Foundations Institute (Item 31))

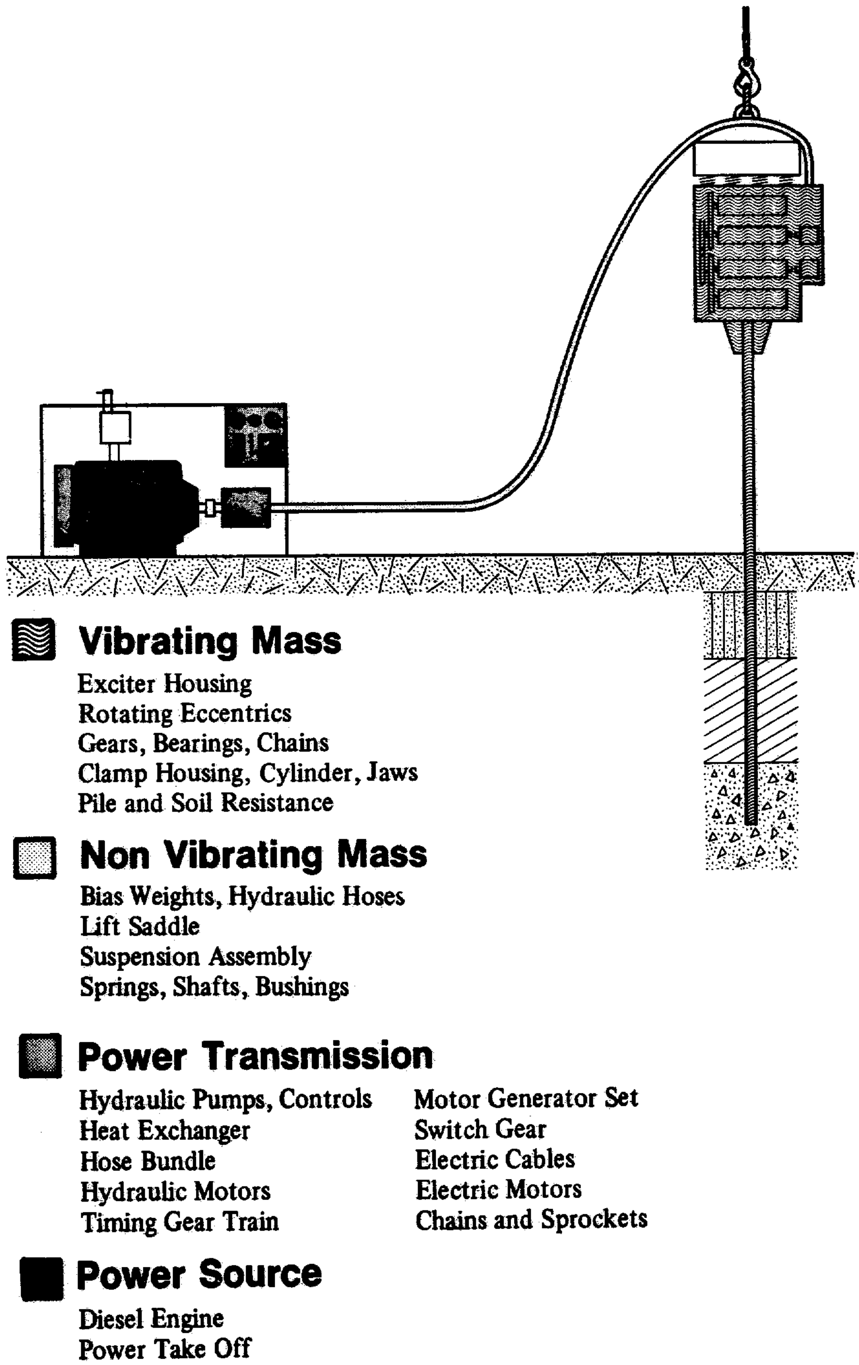


Figure 5-6. Vibratory driver/extractor system (Permission to reprint granted by Deep Foundations Institute (Item 31))

to the double-acting hammer in an inverted position and is powered by compressed air or steam. The vibratory type is a vibratory hammer which is used for extraction, is operated in the same manner as for driving except a steady pulling force is provided and can be as effective as driving. When pulling a pile with either type of extractor, a steady pull must be exerted through the crane line on the pile in the direction of its longitudinal axis to supplement the extractor energy. The lifting line of the crane is attached to the extractor, and the extractor is connected to the pile head with rigid side straps or clamps. This connection must be strong enough to transfer to the pile safely the large forces that are developed by the combined action of the lifting line and the extractor during the pulling operation. If the pile is vertical, or nearly vertical, leads are normally not required for extraction. However, a steeply battered pile would normally require leads to maintain the alignment of the pulling forces along the longitudinal axis of the pile. Effectiveness of the extraction process is directly related to the steady pull exerted by the crane line in the direction of the pile axis plus the efficiency of the extractor. Large hydraulic jacks have occasionally been used to jack piles out of the ground slowly under unusual circumstances, but this method of extraction is not recommended due to the excessive time required and large reaction forces generated.

(3) Leads. Pile driving leads, sometimes called leaders, are usually fabricated of steel and function to align the pile head and hammer concentrically, maintain proper pile position and alignment continuously during the driving operation, and also to provide lateral support for the pile when required. Typical lead systems are shown in Figures 5-7 and 5-8. Proper hammer alignment is extremely important to prevent eccentric loadings on the pile. Otherwise driving energy transferred to the pile may be reduced considerably and structural pile damage due to excessive stresses near the top of the pile may result from eccentric loading. Leads can generally be classified as being either of the fixed or swinging type with several variations of each. Another less widely used type consists of a pipe or beam section that allows the hammer to ride up and down by means of guides attached to the hammer. When driving long slender piles, the use of intermediate pile supports in the leads may be necessary as long unbraced lengths may result in structural damage to the pile and may also contribute to violation of placement and driving tolerances. Leads are not absolutely necessary for every pile-driving operation, but they are normally used to maintain concentric alignment of the pile and hammer, and to obtain required accuracy of pile position and alignment while driving the pile, especially for battered piles. If leads are not required, a suitable template should be provided to maintain the pile in its proper location throughout the driving process. A brief description of fixed leads and swinging leads follows.

(a) Fixed Leads. Fixed leads, also called extended leads, are connected near the top with a horizontal hinge at the tip of the boom and extend somewhat above that point. Near the crane base, a spotter or horizontal brace is normally used and may be hydraulically operated to allow rapid achievement of pile batter. This combination provides maximum control, accuracy and speed when positioning the leads. A much more flexible version is the cardonic fully articulated lead, often called the swivel or three-way lead. Swivels are combined with moon beams or braces to allow movement not only in or out, but also side to side, and rotation of the leads. On large complex jobs which require the installation of a large number of battered piles, it is most advantageous to have leads capable of movement in all directions without having to reposition the entire driving rig. A special version of the fixed lead is the semi-fixed lead, in which the lead is free to move in the up and down direction independently of the crane boom. This type of lead is most beneficial when driving piles into a hole, ditch or over the edge of an excavation. An alternative to the semi-fixed lead is a fixed lead system accompanied by a pony or telescope lead, which secures the hammer in the fixed lead and allows driving below the bottom point of the fixed lead.

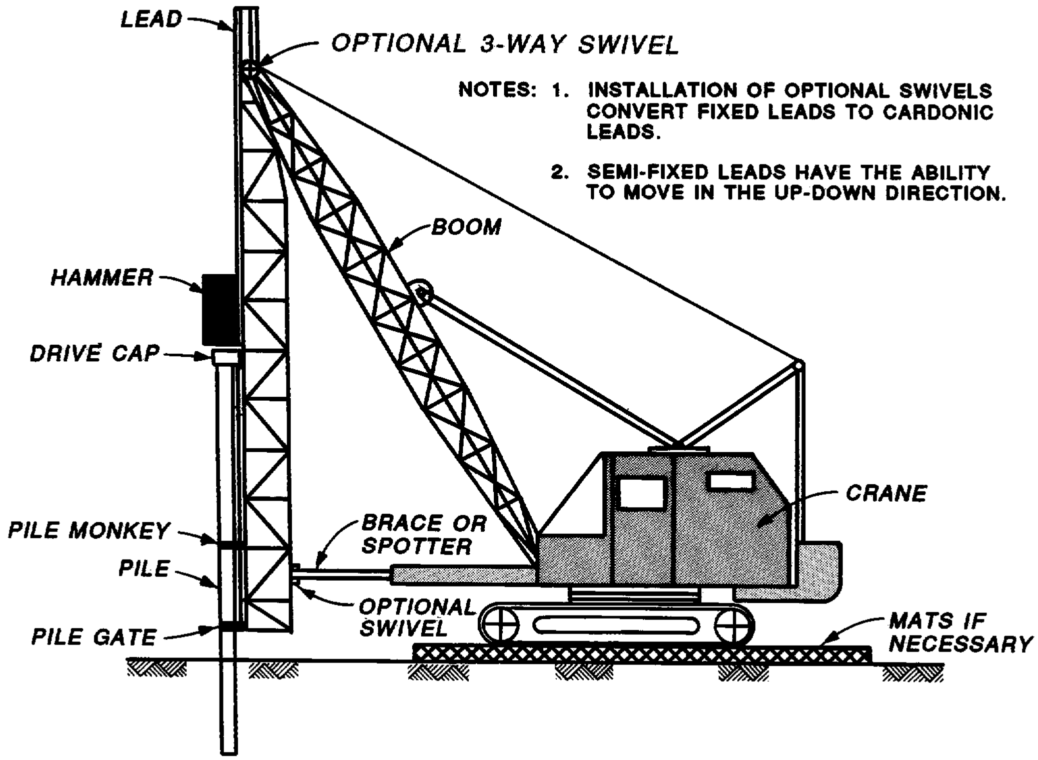


Figure 5-7. Typical fixed or extended leads

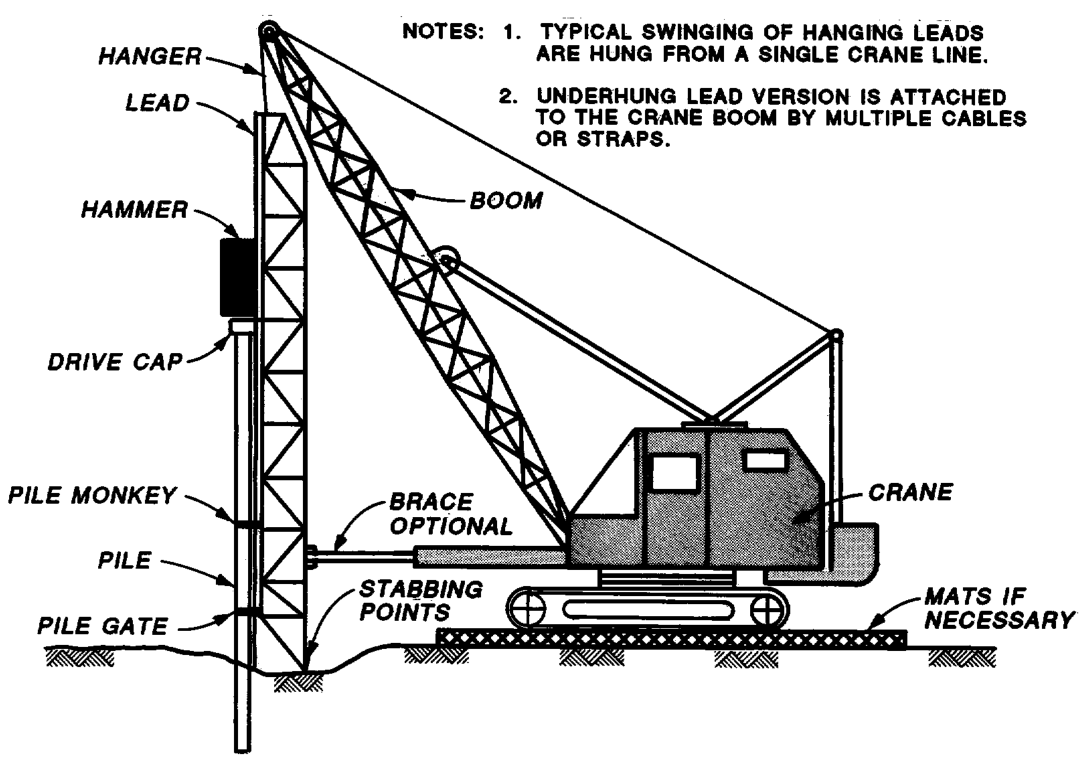


Figure 5-8. Typical swinging lead system

(b) Swinging Leads. The swinging lead, also known as the hanging lead, is hung from the crane boom by a single crane line and permits movement in all directions. A slightly different version is the underhung lead, which hangs from the boom itself by straps or pendant cables. Stabbing points are usually provided at the bottom end of the swinging lead for assistance when fixing position or batter. Swinging leads are lighter, simpler and less expensive than fixed leads, although precise positioning is slow and difficult. If swinging leads are to be used to drive piles that require a high degree of positioning accuracy, a suitable template should be provided to maintain the leads in a steady or fixed position. Leads that are not properly restrained may produce structural damage to piles, particularly concrete piles which are subject to spalling, cracking or even breakage. Swinging leads are especially useful to drive piles in a hole, ditch or over the edge of the excavation.

(4) Driving Caps. The drive cap will be defined here as a complete unit consisting of a helmet, anvil and cushion materials which function to properly transfer the driving energy from the hammer of the pile without damage to the pile. Various sites and types of helmets exist, two of which are shown in Figures 5-9 and 5-10. As impact hammers produce tremendous amounts of impact

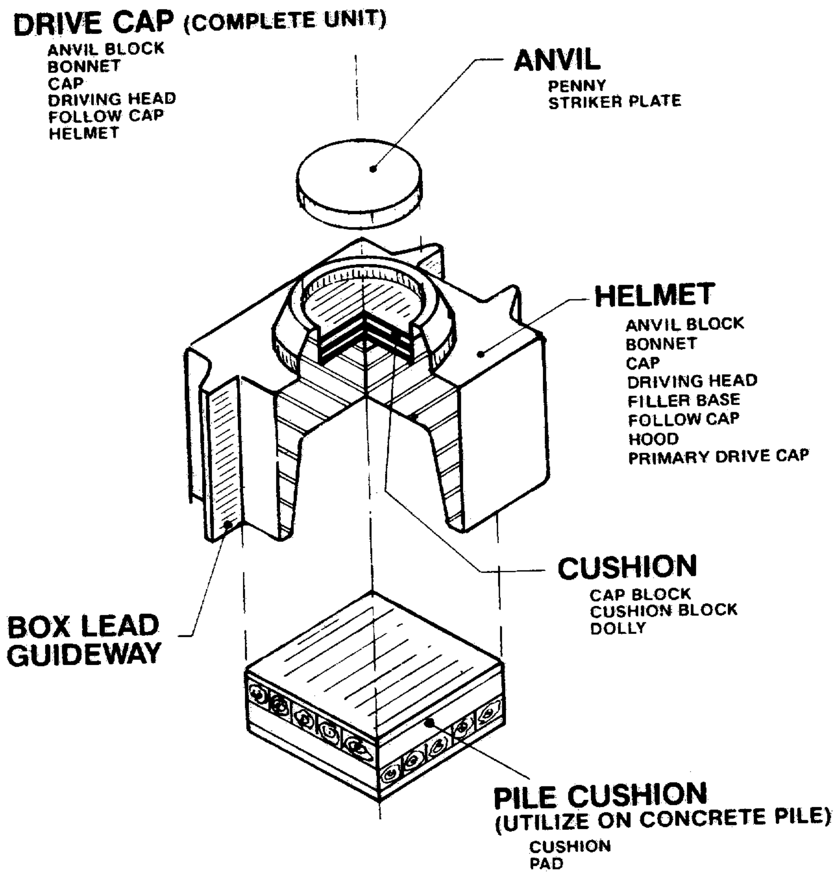


Figure 5-9. Box lead mounting, air/steam and diesel hammers

energy, the hammer blow must be transmitted uniformly over the top of the pile. Driving helmets made of cast steel are used for this purpose and are typically produced by the pile hammer manufacturer to suit its particular equipment. Experience indicates the helmet yields best results when guided by

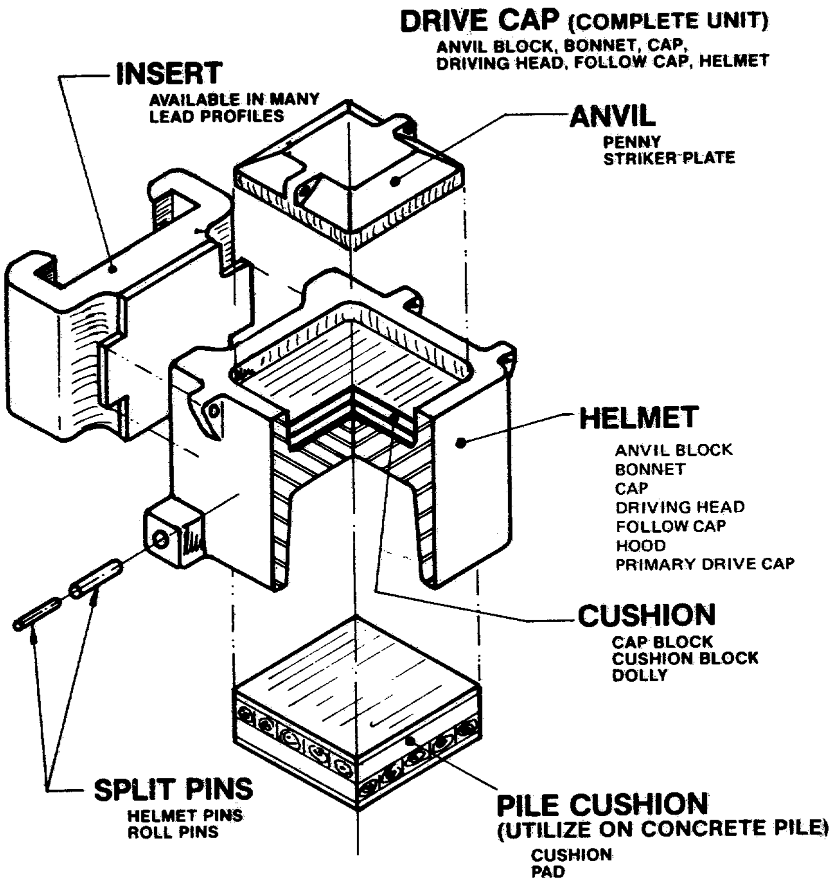


Figure 5-10. Truss lead mounting, generally with diesel hammers

the driving leads, although swinging helmets have proven satisfactory when used with steel-H or heavy walled pipe piles. An appropriate helmet should fit loosely around the pile top to prevent pile restraint by the helmet in cases where the pile tends to rotate during driving. However, the fit should not be so loose that it does not provide alignment of the hammer and pile. While the helmet tends to protect the pile by distributing the blow, the hammer may also require protection from the shock wave reflected back to the hammer. For this purpose, a shock absorbing material known as the hammer cushion is placed between the hammer ram and the helmet. Hammer cushions are required for diesel hammers, while those powered by air or steam may or may not require hammer cushions, depending on the particular hammer type and manufacturer. The hammer cushion also serves to protect the helmet and the pile. Commonly used hammer cushion materials are hardwoods, plywoods, woven steel wire, laminated micarta and aluminum discs, and plastic laminated discs. Thick blocks of hardwood are commonly used but have a tendency to crush, burn and have variable elastic properties during driving. The laminated materials are normally proprietary, provide superior energy transmission characteristics, maintain their elastic properties more uniformly during driving and have a relatively long useful life. The use of materials such as small wood blocks, wood chips, ropes and other materials which allow excessive loss of energy or provide highly erratic properties should be discouraged (or prohibited). Sheet asbestos has been commonly used in the past but is no longer acceptable due to health hazards. A second cushion known as the pile cushion is required when driving concrete piles. This cushion is placed between the helmet and the pile. The pile cushion protects the pile from compressive damage at the head of the pile and can also help control tensile stresses resulting from the tension shock waves produced by driving. Wood materials such as plywood and oak board are most commonly used. A pile cushion is rarely used when driving steel or timber piles. The type and thickness of the hammer and pile cushion materials have a major effect on the energy delivered to the pile. If the contractor chooses too soft a material, excessive energy absorption will result and driving may stall. On the other hand, choosing too hard a material will result in hammer or pile damage. Engineering experience combined with a wave equation analysis is the best method of selecting cushion materials and thicknesses. The complete drive cap design and properties of all components should be submitted by the contractor and reviewed for suitability. Cushion materials require periodic replacement during driving, since their effectiveness is reduced by excessive compression or deterioration. Indications of a need for replacement may be early throttling or bouncing of the hammer, or a ringing sound of the ram. The cushion design is based upon experience to a large extent, and the hammer manufacturer should be consulted in case of questions or distinct problems. Item 34 contains information regarding cushion properties and selection.

(5) Jetting Equipment. Typical equipment consists of jet pipes, a nozzle, pump, engine and hoses. The ensemble of equipment must be capable of providing the desired volume of water at the required pressure. Water volume and pressure must be sufficient to allow discharged water to surface along the sides of the pile. Typical pipe sizes range from 1.5 to 4.0 inches in diameter with nozzles approximately one-half the pipe diameter. Water pressures of 100 to 300 psi are most common but may run as high as 700 psi in isolated cases. Jetting pipes may be encased or cast into the pile, attached to the exterior of the pile or attached to the driving leads and thereby become movable. Moveable jets are preferable, if circumstances do not exclude their use, due to the relative high costs of permanently attached jets. The use of two jets, one on each side the pile, provides the most rapid penetration and best alignment control. When using multiple jets, each should be equipped with its own water source and both should be similarly operated at the same depths and pressures. A single jet placed on one side of the pile may result in excessive pile drift. Experienced personnel should be relied upon when selecting and sizing jetting equipment.

5-3. Pile Driving Studies. Pile driving studies are required for effective design of constructible pile foundations. When evaluating alternative pile types during the design phase, the designer must consider the effects of the pile installation method on the pile and soil capacities and on any existing structures in the proximity of the new foundation. The relative difficulty of driving the piles, and the procedure to determine when each pile has attained adequate capacity to end driving, must also be assessed. Past practices have addressed these considerations by use of empirical dynamic formulas, engineering experience and judgement, review of historical driving data, and various rules of thumb. More recently, the wave equation analysis and the dynamic pile driving analyzer methods have been generally accepted and should be employed. The pile-driving industry is presently moving toward exclusive use of wave equation analysis as the means for a designer to evaluate pile driveability, hammer selection, and limits of penetration. While the wave equation method provides superior analytical techniques, engineering experience and sound judgement are still very much a necessity. A review of pile installations for similar sites and structures can be extremely valuable in that regard. Rules of thumb can still be used for preliminary design and simple projects and should continue to be used during a design office's transition to the wave equation method. The designer must transform the results of these analyses into contract specifications that provide framework for the contractor to select appropriate equipment and installation procedures. Specifications should clearly define the basis of hammer approval, state criteria which will be used to establish the limits of penetration, and exclude installation methods or equipment deemed unsuitable. Analytical predictions are verified in the field by driving and static load tests, or the dynamic analyzer. Three principal topics are discussed in the following paragraphs; wave equation analysis, hammer selection, and penetration limitations. Wave equation results and penetration limitations can and should be used by field personnel to monitor and control the driving operation. In general, these topics are all interrelated.

a. Wave Equation. A wave equation analysis can provide the engineer with two very important items: first, a guide in the selection of properly sized driving equipment and piling to ensure the pile can be driven to final grade without exceeding allowable driving stresses; and secondly, a penetration rate expressed as a minimum number of blows per inch of penetration for impact hammers to determine when the pile has been driven sufficiently to develop the required capacity. This can be presented graphically by depicting the relationships between blows/inch (driving resistance) and ultimate static soil resistance (pile capacity) and blows/inch versus structural stresses in the pile. The graphs can then be used by field personnel and the contractor to monitor driving. When using the analysis results during installation, the design engineer must make certain that assumed design parameter values closely correspond to the actual values encountered in the field. This correlation can be accomplished by utilizing the load capacity and load transfer distribution obtained from static load tests and the dynamic analyzer. Analysis is based on a specific type and length of pile, and a driving system operating at an assumed efficiency in a modeled soil stratification. The results are applicable only to the assumed system and should only be used for the length of pile investigated. Incremental analysis is typically performed where the length of pile embedded into the ground is varied. Design application requires sound engineering judgement and experience where parameter (hammer, drive cap, pile and soil resistance) sensitivity is concerned. Research has shown that published hammer efficiencies (by the manufacturer) tend to significantly overestimate the energy actually absorbed by the pile in the field. Efficiency is also affected by placing the hammer on a batter and this can be a major source of error. Diesel hammers may have a variable stroke and a bracket analysis is strongly recommended. Hammer efficiency can be field-verified by good inspection techniques and more accurately by use of a dynamic pile analyzer. Data obtained from the wave equation analysis should be used with judgement for friction piles since pile set-up may occur. Data generated using the dynamic analyzer during original driving will not reflect pile set-up and may under-predict a pile's capacity. To produce data that reflect the true capacity of the pile, the pile should be restruck after set-up has occurred, usually a minimum of 14 days after initial driving. A wave equation analysis is recommended for all but the simplest of projects for which the designers have experience and should be performed for predicting behavior during design and confirming pile performance during construction of a project. The wave equation computer program "WEAP" (Wave Equation Analysis of Pile Driving) is available to Corps of Engineers offices. Item 34 contains an excellent discussion of wave propagation theory and its application to pile foundations.

b. Hammer Selection.

(1) General. Hammer selection may be the most important aspect of pile installation. In some installations only one hammer type may be applicable for the pile-soil combination, while for others several types may suitable. Evaluation must consider the need to use pile penetration rate as the means to end driving, the ability to drive the pile without structural damage or reducing soil capacity, the ability to obtain penetration rates within the desired band, and the realization that some hammer types may cause reduced capacities for identical pile lengths. In general, wave equation analysis supplemented by engineering experience and judgement should be the basis for hammer approval and criteria such as allowable driving stresses, desired penetration rates, and any other data used as a basis for approval that are clearly defined in the specifications. Wave equation analysis should normally be performed by the Government, and data that the contractor are required to submit must be clearly defined. Contractor disagreements with the Government's analysis can be contested by the contractor and resolved at his expense through resubmittals performed and sealed by a registered engineer, by field verification of driving and load tests, and by other methods approved by the design engineer.

(2) Size selection for a particular hammer must consider the pile's anticipated driving resistance, ultimate capacity, pile stresses expected during driving, and pile set-up. The hammer type and size used for production should always match that used in the test program because a different hammer would most likely result in a different capacity. The designer or contractor may designate a number of hammers for the test program when warranted. Any changes in hammer type or size will usually require additional testing.

(3) Prior to the wave equation method and development of the desk top computer, hammers were typically chosen based on dynamic formulas, rules of thumb, minimum energy rating based on pile type or load capacity, and methods which equated the pile weight to the weight of the moving hammer parts. These methods were primarily derived from experience and still have a place in hammer selection. However, these methods are only recommended as secondary procedures. Dynamic formulas are not recommended due to the lack of reliability and are considered to be inferior to the wave equation method. Table 5-1 is presented for information purposes only and to illustrate one of the many empirical methods still in use today. Tables such as this are generally being phased out and replaced by the wave equation method and sometimes supplemented by dynamic analysis in the field. These methods can and should still be utilized in an office in transition to the wave equation method.

(4) Vibratory hammers require special attention as they have been shown to yield reduced capacity at work loads in some cases (Item 10, Item 15). Another reason for special attention is that there is no reliable way to evaluate driving resistance and driving induced stresses in piles as can be done for impact driven piles via pile driving analyzer and wave equation analysis. However, the potential economic advantage of a vibratory hammer cannot be discounted without adequate consideration, especially for large projects. Specifications can be written to require dual driving and load test programs if needed to address additional pile length and penetration

TABLE 5-1

SUGGESTED MINIMUM HAMMER ENERGY - IMPACT HAMMERS
(Taken from ARMY TM 5-849-1, May 1982)

Class I - Timber Piles	
Capacity to 20 Tons	- 7,500 ft-lb
Capacity over 20 Tons to 25 Tons	- 9,000 ft-lb (Single-acting hammers) - 14,000 ft-lb (Double-acting hammers)
Capacity over 25 Tons	- 12,000 ft-lb (Single-acting hammers) - 14,000 ft-lb (Double-acting hammers)
Class II - Concrete and Steel Piles	
Capacities to 60 Tons	- 15,000 ft-lb
Capacities over 60 Tons	- 19,000 ft-lb

limitations. Other engineering and construction agencies have permitted the use of a vibratory hammer but require a percentage of production piles be driven or struck with an impact hammer to determine relative capacity. In cases where tests indicate that additional pile length can be attributed to the hammer type, increased cost should be the responsibility of the contractor. The contractor may determine if the additional cost for testing and monitoring would be offset by increased production rate.

c. Penetration Limitations. For impact hammers the rate of penetration is customarily defined as the blow count per unit length of pile penetration. Blow counts are typically recorded in the field on a per-foot basis until the pile approaches a designated tip elevation or the end of driving. At that point the blow count is usually recorded for each inch of penetration. Limiting penetration rates are designated to prevent overdriving, which may cause structural damage to the pile, and to provide guidance for determining the relative capacity attained during driving. Pile tip damage due to very difficult driving (commonly referred to as refusal) is not readily detectable when the pile encounters an obstruction or a hard bearing stratum prior to reaching the indicated tip elevation. Therefore, the limiting penetration rates, or the criteria necessary to determine limiting rates, should be specified. Rules of thumb, used to avoid structural damage, derived through experience and generally accepted by most engineers are listed in Table 5-2.

Table 5-2

Limiting Penetration Rates

Pile Type	Maximum Blow Count (blows per inch)
Timber	3-4
Concrete	10
Steel Pipe	10-20
Steel -H	10-20

The limiting penetration rates generally should be established by the Government and based upon results of wave equation analysis that have been correlated with results obtained from use of a pile driving analyzer during driving the test piles and the results of static load tests. Piles that derive their primary support from friction are driven to a predetermined tip elevation. For friction piles, the required length of penetration or tip elevation is determined from geotechnical data and capacity from test piles. The results of static load tests are then used to adjust the specified tip elevation or penetration length. Applicable penetration rate limits are compared with the rates encountered when driving the piles for the static load tests and adjusted if necessary. Piles that derive their primary support from end bearing in a hard soil layer or rock typically require a verification of load capacity, which may be indicated by the penetration rate. In this case the pile is normally driven to a specified blow count rather than a predetermined length. Once again, this blow count can best be obtained from wave equation analyses that have been correlated with driving and static load test data. Refinements in the wave equation analyses should be made by use of the pile dynamic analyzer when pile load test are not economically feasible. In either event the pile driving analyzer can be used to monitor the installation of piling. The designer should be wary that penetration rates observed in the field can easily be distorted by erratic or malfunctioning equipment and improper contractor operations. Distorted rates can be frequently attributed to an erratic or poorly maintained hammer, poor alignment of the hammer and pile, erratically behaving cushion materials, changing of a cushion near the end of driving, and noncontinuous driving that may allow the pile to set up and gain strength. A driven pile that has failed to acquire a specified tip elevation or penetration rate must be reanalyzed by the designer. If the safety factor for the pile or group is jeopardized, remedial measures are necessary, including extension of the driven pile by a splice, replacement of the pile with a longer one, or the addition of a sister pile. An end-bearing pile that stops short of its bearing stratum may be a candidate for special driving assistance, as discussed in paragraph 5-2a(3).

5-4. Control of Pile Driving Operations. Field installation requires continuous monitoring to ensure that an adequate foundation is achieved. All facets of installation require examination, from storage and handling to end of driving. If it is assumed that equipment is properly utilized and working at an efficient level, there remain two areas of concern: (1) monitoring installation to prevent structural damage, and (2) acquiring data to ensure that adequate capacity is obtained. Paragraph 5-3c previously discussed the use of wave equation analysis and selection of penetration limits in that regard. Field monitoring can be supplemented by dynamic analysis which can refine several assumptions made in the wave equation analysis (e.g. energy transfer to the pile), evaluate equipment performance, determine pile stresses estimated, and detect pile breakage. Piles suspected of sustaining structural damage or lacking in capacity can be further investigated by extraction or load testing.

a. Pile Driving Analyzers. These devices give a general indication of capacity, measure hammer and cushion performance and pile stresses from measurements of applied force and acceleration at the head of the pile. Capacity can often be inferred from the measurements using a simple damping constant for the soil. The soil damping constants can be calibrated from static load tests or by using special wave equation programs designed to infer capacity from pile-head measurements. The equipment is highly portable, performs most calculations on the job site, and requires trained and experienced personnel to operate. Analyzers are helpful to establish driving criteria and provide construction quality control when used in combination with static pile load test. The pile driving analyzer can be used in conjunction with theoretical predictions where static pile tests are not economically justified. Experience and sound engineering judgement are required when determining whether or not to use dynamic analyzers on a job, since this is a site-dependent decision. As previously stated, the analyzer only yields results of estimated capacity for the specific blow recorded, i.e., if data are taken during initial driving, the results can be distorted due to locked-in residual stresses, and any gain in capacity with time (set-up) is not accounted for. To account for the time-dependent gain in capacity, the pile should be restruck after a specified time (e.g. 7 to 14 days) has elapsed. If correlated with static pile tests and good driving records, the pile driving analyzer may be used successfully to predict capacity of production piles. It may also be used to indicate hammer efficiency, driving energy delivered to the pile or indicate pile breakage during driving. Specifications must address contractor and Government responsibilities when using a dynamic analyzer.

b. Records. Examples of the minimum records to be kept during driving are contained in Figures 5-11 and 5-12. The blow count per foot of pile penetration and the amount of free run drop under the hammer weight are two very obvious pieces of data to collect. When driving data are being analyzed, common questions are: the hammer type, manufacturer and any identifying numbers, has the hammer been modified in any way, was the hammer working at its rated capacity, cushion material and thickness, pile length and size, date of casting if precast concrete, depth of penetration, was driving continuous, were any special efforts of installation such as jetting or preboring applied, type of connection to the pile, magnitude of bias load, and the method and location of any splices. For vibratory hammers, the operating frequency, horsepower applied, and rate of penetration should also be recorded. Any occurrence of heave or subsidence for both the ground surface and adjacent piles should be noted. The method of hauling, storing, and handling the pile should also be recorded. Another item which should be recorded is whether or not the pile was properly handled as it was raised into the leads of the pile driver. Such records of data are invaluable when problems arise, performing as-built analysis and resolving contract disputes involving claims or litigation.

c. Proof Tests. Proof tests may become necessary if damage to a pile is suspected during handling or driving. Proof testing may also be prudent when large numbers of piles are driven into soils with highly variable stratification, and the driving records contain erratic data which can not be explained

PILE DRIVING REPORT

PROJECT Golden Meadon Flood Gate

CONTRACTOR Bosick Construction

HAMMER:

MAKE & MODEL Conmaco 115

WT. RAM 11500 STROKE 3'

ENERGY DELIVERED 37375

DESCRIPTION AND DIMENSIONS OF DRIVING CAP 14" x 14" (K) 1770 lb

SPEED: RATED MEASURED 49

STEAM OR AIR PRESSURE: AT HAMMER ______ AT BOILER 128 psi

JETTING PRESSURE AND ELEVATIONS:
Predrilling: Size & Depth

PILE NO. 4 FS

LOCATION East Floodside

TYPE: Prestress Concrete

DIMENSIONS 14 x 14 x 83.4

LENGTH IN LEADS 100

BATTER 1 ON (5)

ELEVATION OF GROUND -14.0

ELEVATION OF CUT-OFF -4.98

ELEVATION OF PILE TIP -71.4

ELEVATION OF SPLICES None

INSPECTOR Fisher DATE 11/7/83

TIME: START DRIVING 14:49 FINISH DRIVING 14:53 DRIVING TIME 4 min

INTERRUPTIONS (TIME, TIP ELEV. & REASON) 14:52 unhook piling

DRIVING RESISTANCE

FT	NO. OF BLOWS	FT	NO. OF BLOWS	FT	NO. OF BLOWS	FT	NO. OF BLOWS	FT	NO. OF BLOWS	FT	NO. OF BLOWS	FT	NO. OF BLOWS
0		15		30	2	45	5	60	2	75		90	
1		16		31	3	46	5	61	2	76		91	
2		17		32	3	47	5	62	2	77		92	
3		18		33	3	48	5	63	2	78		93	
4		19		34	3	49	4	64	2	79		94	
5		20		35	4	50	3	65	3	80		95	
6		21		36	5	51	4	66	2	81		96	
7		22		37	7	52	3	67	3	82		97	
8		23		38	6	53	3	68	3	83		98	
9		24	1	39	10	54	3	69	3	84		99	
10		25	1	40	10	55	3	70	3	85		100	
11		26	1	41	11	56	2	71	3	86		101	
12		27	2	42	12	57	2	72	3	87		102	
13		28	2	43	10	58	2	73	4	88		103	
14		29	2	44	5	59	2	74	100	89		104	

BLOWS/INCH FOR LAST FOOT OF DRIVING

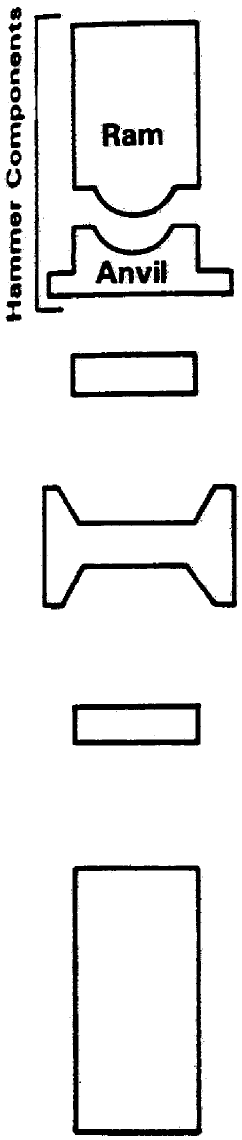
FT	NO. OF BLOWS
1	4
2	6
3	6
4	8
5	8
6	8
7	10
8	10
9	10
10	10
11	10
12	10

Figure 5-11. Example of a completed Pile Driving Record

Project: ____________________

Structure Name ____________________

Pile Driving Contractor or Subcontractor: ____________________
(Piles driven by)



Hammer

Manufacturer: __________ Model: __________
Type: __________ Serial No.: __________
Rated Energy: __________ at __________ Length of Stroke
Modifications: ____________________

Capblock (Hammer Cushion)

Material: ____________________
Thickness __________ Area: __________
Modulus of Elasticity — E __________ (P.S.I.)
Coefficient of Restitution-e ____________________

Pile Cap — Helmet / Bonnet / Anvil Block / Drivehead — Weight: ____________________

Pile Cushion

Cushion Material: ____________________
Thickness: __________ Area: __________
Modulus of Elasticity — E __________ (P.S.I.)
Coefficient of Restitution ____________________

Pile

Pile Type: ____________________
Length (in Leads) — ____________________
Weight/ft. ____________________
Wall Thickness: __________ Taper: __________
Cross Sectional Area __________ in^2
Design Pile Capacity: __________ (Tons)
Description of Splice: ____________________
Tip Treatment Description: ____________________

Note: If mandrel is used to drive the pile, attach separate manufacturer's detail sheet(s) including weight and dimensions.

Figure 5-12. Example of a typical Pile Driving Equipment Report (Permission to reprint granted by Deep Foundations Institute (Item 31)) by the contractor's operations. An equally important indicator may be failure of a pile to reach the prescribed tip elevation or rate of penetration. Different types of proof testing can be employed depending upon the problem suspected. Testing with the pile driving analyzer may be performed by restriking previously driven piles, or data may be generated during driving and used in a wave equation analysis. A static quick load test, ASTM D1143-81 (Item 25), may also be used to determine the ultimate load carrying capacity of piles. On projects where it is anticipated that proof testing will be required, it is recommended that a line item be included in the bid schedule for performing such.

d. Extraction for Inspection. Piles are subject to structural damage during the driving process. Suspected damage below the ground surface would be cause for extracting a pile. Typical indicators are a pile suddenly drifting off location, erratic driving unexplained by the soil stratification, a sudden decrease in the driving resistance indicating breakage of the pile, or possible pile interference indicated by sound or vibration of nearby piles. Damage at the pile head may or may not indicate damage near the pile tip. If pile damage is suspected, the pile should be extracted and visually inspected. However, both the designer and field engineer should be cognizant of the fact that high costs and additional problems may be incurred as a result of extraction. For instance, a perfectly good pile may be damaged during the extraction procedure, particularly when extracting concrete piles, and soil stress states can be adversely modified around nearby piles where the subject pile is in a group. Costs associated with additional driving rig moves, obtaining and setting up extraction equipment, redriving time delays, and engineering and administrative costs are normally claimed by the contractor.

5-5. Results of Corps Experience.

a. Generalized Principles. The Corps of Engineers has been responsible for the design of construction of numerous foundations during the past 40 to 50 years. Through the efforts of Corps engineers, design and construction consultants, researchers, construction and individual contractors, the Corps has acquired vast experience in the foundation field. Advantage should be taken of this experience by researching available technical literature such as WES reports, engineering manuals, technical letters, project completion reports, contract specifications, design documents and verbal communications with other offices. Both the foundation design and constructability can benefit from this experience and historical data. Case histories of similar projects and similar sites are extremely valuable in this regard.

b. Case History. A typical case history for a recent project is presented in Appendix C.

c. Augmenting the Q/C and Q/A Processes. Providing for suitable controls during the construction process is an essential part of foundation design and contract preparation. Engineering judgement and past experience are required to determine the appropriate construction control procedures and methods for a particular type of pile foundation and soil system. The details of the construction controls should be developed during the foundation design process, tested during driving of test piles, and finalized upon evaluation of pile load test results. Proposed methods should be included in the design memoranda with proposed instrumentation and should reflect the functional importance and economic parameters of the project. An attempt should be made to anticipate and address all possible situations that may be encountered during pile driving and that could have a detrimental effect on the serviceability of the foundation. Adverse conditions are explained in paragraph 2-7 (and throughout this manual) and include pile material and geometry, subsurface conditions, driving equipment, and miscellaneous items.

(1) Pile material and geometry include defective pile material, strength, dimensions, straightness, spacing, alinement, location, etc.

(2) Subsurface conditions refer to strata variation, voids, liquefaction, obstruction, heave, densification, downdrag, water table, etc.

(3) Driving equipment pertains to defects in hammer, loads, accessories, etc.

(4) Miscellaneous items are vibration, adjacent structures or utilities, erratic values from PDA compared with wave equation results, etc.

5-6. As-Built Analysis.

a. Structural. Several variables may cause the actual pile foundation to differ from the initial design both in geometry (affecting pile loads) and pile capacities. The effects of these variations should be evaluated as discussed in paragraph 4-7i.

(1) Pile Geometry. As reflected by the relatively lenient driving tolerances normally allowed for pile position, orientation, and batter, physical control of the individual piles during driving is very difficult due to the nature of the large equipment required. Initial positioning and orientation of the pile in preparation for driving is not precise, and individual piles may have various amounts of initial camber and warp. During driving, variations in soil resistance combined with necessary clearances between the pile and the guides in the leads, and between the pile and hammer components (driving head or helmet, cushioning material, and hammer ram), permit variations in pile position and orientation. Small variations may be substantially amplified by long piles that are relatively flexible, by large pile batters, and by unexpected obstructions encountered in the soil during driving. Any combination of the aforementioned variables may result in differences between the design and the actual geometry of the resulting pile foundation. Variations in initial pile positioning and drifting of the pile during driving will each affect the final position and orientation of the head, the longitudinal axis, and the tip of the driven pile. The final position, orientation and batter of the pile head can be accurately measured after driving. However, the variation in orientation of the pile axis (curvature, twist, batter angle, and direction) and the pile tip elevation cannot be accurately determined after driving. If a pile is extracted for inspection and is undamaged, the axis orientation and tip elevation may be closely approximated for that pile as previously driven by extrapolation from measurements at the pile head.

(2) Pile Capacity. The pile capacity (axial, lateral, and buckling) is an interactive function of the properties of the soil and the pile, both governed by pile length. Also, the design length is determined by the batter angle and tip elevation. The batter angle may be affected by the unknown drift, which also affects the tip elevation. Variations in driving resistance may cause a substantial variation from design tip elevation. Based on

static pile load test results, a tip elevation is specified to provide the estimated design capacity and safety factor for the service piles. In addition, a minimum driving resistance (minimum blow count rate) required to develop the pile capacity and a maximum driving resistance that may be tolerated without structural damage to the piles are usually specified for guidance during driving. When the pile has been driven to the required tip elevation and the minimum driving resistance has not been developed, the pile may be extended by splicing and driven until the indicated driving resistance is developed, if deemed necessary. If the maximum driving resistance is developed prior to the pile’s being driven to the design tip elevation, the situation must be investigated to determine the cause of the resistance (subsurface obstruction, gravel or cobbles, improper driving, etc.) When the cause has been determined, a decision must be made either to extract the pile and redrive it in another location, to leave the pile intact and cut off the upper portion, or to continue driving with a modified procedure or an increased maximum resistance parameter.

b. Geotechnical. As adjacent piles are generally driven into progressively denser materials, some piles driven previously may heave. Heave, which can be measured with quality surveying techniques, is detrimental to the performance of the pile foundation. Heave can be minimized by using the largest possible spacing between piles. Soil movements can be detected 5 feet to 8 pile diameters away from a pile, and a pile spacing of 3 diameters or less is not recommended. This problem can best be avoided by greater center-to-center spacing and driving radially outward from the center of the foundation. If significant heave occurs, the pile hammer should be replaced on the pile and the pile redriven. Since the pile can easily be damaged during this operation, the design engineer specifies driving energy or blow count that should not be exceeded. When the necessity for redriving develops during driving operations, the design engineer should evaluate and modify the driving sequence in an attempt to minimize the heave effect. When installation problems, especially heave, might conceivably occur while driving the piles, no pile head should be cut off until a sufficient number of piles have been driven or the driving operation has progressed for a sufficient distance to ascertain that problems will not be encountered or that the driving operation will no longer affect the driven piles. For any pile driven short of the specified tip elevation, the capacity should be recomputed and a safety factor estimated for the design load. If a significant number of piles, or a group of piles clustered together, are found to have less than the required safety factor, the structure should be reanalyzed using the recomputed capacity.

c. Wave Equation and Pile Driving Analyzer. Both of these are tools available to the pile foundation designer to evaluate his theoretical design from a constructability standpoint or to evaluate the as-built pile foundation. The pile driving analyzer is extremely useful in evaluating the field installation procedures. If used in conjunction with static load tests for correlation, it may be useful in evaluating the further installation of production piles. The pile driving analyzer, may be used to evaluate the pile hammer efficiency and to evaluate or detect potentially damaged piles. In using the pile driving analyzer, it should be noted that the analyzer uses dynamic theory to infer static pile capacity. In some soils the pile develops a significant portion of its ability to carry load after it has set-up for a period of time, therefore in such a case the pile should be restruck after this set-up has been allowed to occur. In general, a set-up period of 14 days is considered sufficient. The wave equation allows the dynamic analysis of the pile, soil, and driving equipment to be evaluated as a system, thereby allowing the designer to evaluate variables such as the pile cushion, the hammer, or even the pile material. The wave equation is a valuable tool that can be used to evaluate proposed methods for pile installation during design or construction, i.e., if the contractor proposes a hammer system to install a pile, this program can evaluate the data and aid in detecting potential problems or deficiencies.

5-7. Field Evaluation.

a. Driving Operations. The design engineers (structural and geotechnical) should visit the construction site while service piles are being driven to observe the driving operation and to investigate any difficulty that is encountered. The driving equipment should be inspected, and field conditions should be checked. Proposed methods for storage and handling of piles, positioning and aligning piles, supporting piles in leads, and transferring hammer energy to piles should be checked prior to driving the first pile. Driving of the first few piles should be observed to assure compliance with approved methods, proper operation of equipment (per manufacturer's rating) and proper driving procedures. In addition, the observer should watch for abnormal driving resistances and the occurrence of pile heave or voids adjacent to driven piles. When unusual difficulties develop, driving should again be observed and compared with the initial set of observations. The blow count for the piles should be plotted during the installation process to detect broken or damaged piles. Drastic drops in blow counts of similar piles in similar soils would be an indication of broken piles. It is also recommended that the blows per minute of hammer operation be recorded to indicate the efficiency of a hammer, since reduced rates often indicate reduced efficiency.

b. Pile Positioning. When pile driving has been satisfactorily completed, the actual position, orientation, and batter of each pile should be measured (extrapolating from head measurements) and compared with the design geometry. If substantial variations are found, an as-built analysis may be required, as discussed in paragraph 4-7i. If there is substantial variation from the design tip elevation or from the anticipated driving resistance, the pile capacities should be re-evaluated. The piles may be inspected for drifting, which would be evidenced by voids adjacent to the pile. Drifting could be caused by striking a hard underground object or another pile. (A change in the impact sound of the pile during driving can be used to detect piles striking an obstruction.) It is also recommended that the blows per minute of hammer operation be recorded to indicate the efficiency of a hammer. The blow count records should be studied while driving is ongoing.

c. Static Loading. Prior to static load test, the jack and load cell should be checked, and the load settlement data should be plotted and checked in the field during the test.